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Treating the Impacts of Connecting HVDC Link Converters with AC Power System Using Real-Time Active Power Quality Unit

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ABSTRACT

The High Voltage Direct Current (HVDC) systems have been applied worldwide, due to important roles, technical benefits, and high efficiency. Usually, the HVDC network is a joining link between two separate and different technical properties of HVAC systems, which enhances its use. The joinpoint system that used to connect HVDC and HVAC links is a controlled converter circuit. Despite the importance of use and the significant benefits of the HVDC link, there are negative effects on the power quality of the electrical power of both systems connected on both ends of the HVDC network. The low quality of electric power has been addressed by known methods, whether traditional or modern. But the improvement is usually made with the assumption of load conditions and the need for the system to synthesize it. This research presents an innovative method based on real-time control strategy. This is performed by proposing dSPACE for controlling the Active Power Quality Unit (APQU). The proposed control strategy of the APQU includes a Modified Harmonics Pulse Width Modulation (MHPWM) algorithm in order to mitigate the line current THD and improve the effective power factor of the AC converter sides. The MHPWM is applicable for different nonlinear loads and can be implemented with APQU based on different topologies of H-bridge voltage source inverter. Simulation and practical results have been presented in this paper. The Experimental results are done based on real-time laboratory tests using dSPACE DS1103 board as a controller circuit. The presented results, under different operating loading conditions, show that the APQU provides almost unity power factor and significantly improving THD of the AC supply currents at both sides of the HVDC link controlled converters.

1. Introduction

High voltage DC (HVDC) systems have been applied, since 1950, as an alternative way of exchange transferring electrical power between two far locations of source power stations [1, 2]. The HVDC systems have been used in worldwide due to important roles, technical benefits, and high efficiency. Usually, the HVDC network is a joining link between two separate and different technical properties of HVAC systems which enhances its use. A controlled converter circuit is used as a joinpoint. Different types and topologies of the HVDC circuit are widely used, and mainly can be divided into two categories. These categories are the line commutated converter (LCC) and the voltage source converter (VSC) [3]. This research adopts the first category of LCC–HVDC system. Despite the importance of use and the significant benefits of the HVDC link, there are negative effects on the power quality of the AC electrical power of both systems connected at both ends of the HVDC network. The low quality of this type of utility has been addressed by known methods, whether traditional or modern [4]. But the improvement is usually made with the assumption of certain loading conditions and the need for the system to synthesize it. The traditional methods using passive power filter (PPF) to mitigate the significant harmonic components. Also using higher converter pulse topology will eliminate low order harmonics.

Nowadays, there are several LCC–HVDC transmission systems working in China. Although the VSC–HVDC transmission system has been used and considered to be better economically than the LCC–HVDC transmission system for low and medium power applications. The LCC–HVDC transmission system cannot be dispensed with in countries that use this system. The LCC–HVDC is more reliable than VSC–HVDC in high power transmission with consideration the cost and reliability [5]. In HVDC systems, different types of filters are used. In 1997 [6], hybrid filters were used for reactive-power compensation and harmonics reduction at the AC side of the CIGRÉ benchmark system. A PPF with an active part connected to the Tjele HVDC transmission system

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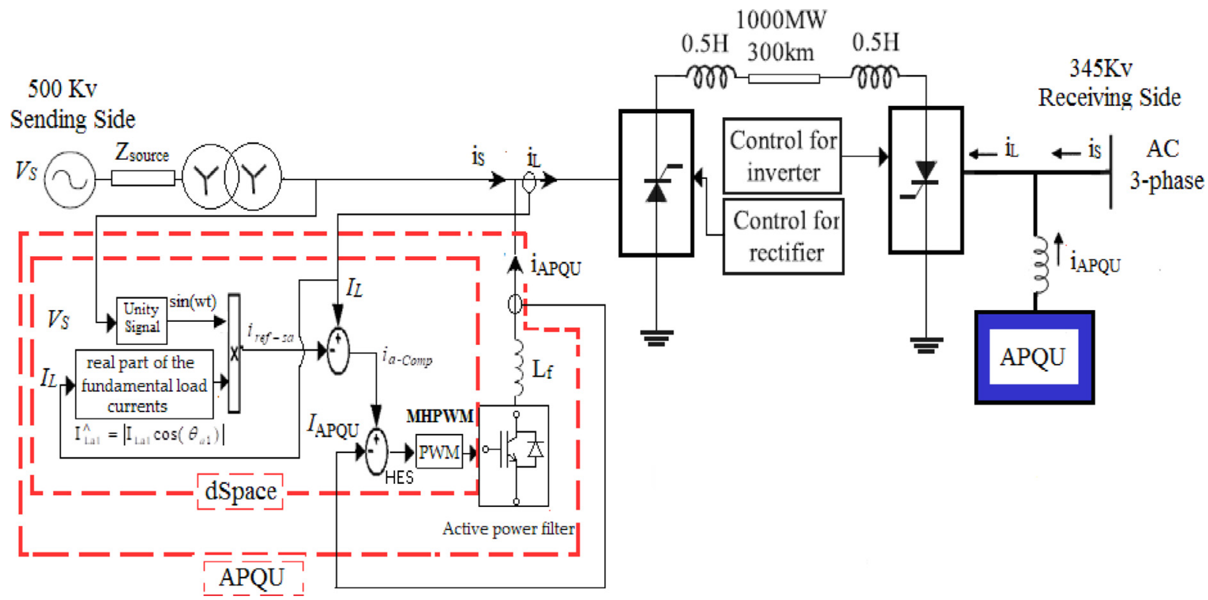


Fig. 1. Six-pulse LCC–HVDC system with the APQU and MHPWM control circuit per phase.

project in Denmark was implemented in 2001 [7]. The filter was designed to eliminate harmonics from the 5th up to the 49th. At the same time, an active power filter (APF) coupling through a transformer and a band-pass filter designed by [8] was used to absorb the 11th and the 13th harmonic currents generated by the 12-pulse capacitor commutated converter HVDC link. Beside the coupling filter, a high pass filter was used to absorb higher order harmonics. In 2007 [9], a damped-type double tuned filter was designed to improve the power quality of a 6-pulse controlled HVDC converter. The parameters of the damped-type double tuned filter were calculated depending on the reactive power consumed and parallel resonance frequencies. In 2012 [10] PPF and a modified APF (MAPF) were used to improve the power quality of the 12-pluse LCC–HVDC system. The MAPF is dynamically controlled based on a modified harmonics PWM (MHPWM) algorithm. PPF results are within limits for a certain value of dc power flow. While the MAPF performs better for different values of dc power flow. In the same year [11, 12], the MAPF based on 5-level and 7-level cascade H-bridge inverter using MHPWM algorithm as a controller was used to reduce harmonics and correct effective input power factor (PF), at the same time, at both AC-sides of the 6-pulse LCC–HVDC system. The proposed filter is suitable in stable and steady state operating conditions. PF results are around unity for different dc power flow levels, while THD results are significantly reduced at both AC sides. In 2017 [13], the harmonics current path in a modular multi-level converter based HVDC transmission was analysed. The control circuit of a modular multi-level converter was suggested to suppress AC and DC harmonics. APFs with 2-level and multilevel voltage source inverter (VSI) have been implemented for different applications with nonlinear loads [14, 15]. In 2018 [16], a three-phase three-level neutral point clamped inverter with its controller was design. The system was modelled and implemented experimental to explain the system compensation performance during steady-state and dynamic condition. In 2019 [17], a hybrid energy system based on PV-Wind-Fuel cell was tested under balanced and unbalanced nonlinear loads. The suggested system was built to improve the power system quality and power grid performance based on renewable energy sources. In 2020 [18], a 24-pulse thyristor converter was used in HVDC transmission system. The system was simulated and implemented experimentally under normal and abnormal conditions to mitigate harmonics and improve power system quality. While in same year [19], a 3000 MVA hybrid HVDC transmission system based on LCC and alternate arm converter was established.

Recent development in power switching devices, digital electronics, and programmable equipment have been contributed in increasing the interest in utilizing APFs. The digital processing control of an APF can be designed in time or frequency domain and may be based on open or closed loop control techniques. Designing a control system for an APF in the time domain is usually done based on synchronous frame (d-q) method [20], instantaneous power theory (p-q) [21] and synchronous flux detection algorithm [22].

As a continuance of the previous study to get a complete understanding of power quality improvement in HVDC transmission systems, an active power quality unit (APQU) circuit has been employed in this paper. The APQU is employing APF with a new control strategy for improving the power quality of a 6-pulse LCC–HVDC transmission system. The MHPWM algorithm is used to drive the APQU. Therefore, improving the power quality in the 6-pulse LCC–HVDC transmission system is very important. The APQU system is used for this reason. The novelty of the proposed APQU is to work as harmonics compensator and PF corrector for different level of DC power flow through transmission system

2. Theoretical analysis of the proposed active power qulity unit

The APQU is designed based on three-phase 2-level VSI, 5-level cascaded H-bridge VSI (5-LCHBVSI), and 7-level (7-LCHBVSI). The MHPWM algorithm suggested by [10–12] is built to control the APQU circuit. The APQU with its controller is made to produce random harmonic injection and compensate the reactive power at both AC sides of the 6-pulse LCC–HVDC link. This means that the APCU is behaving as a compensation unit, for both reactive power and harmonic components, for various dc power flow through the transmission line. According to this feature, the system is formed to improve the power quality of the 6-pulse LCC–HVDC transmission system as shown in Fig. 1.

In this algorithm, the fundamental real part value of the load current ($\hat{I}_{La1}$, $\hat{I}_{Lb1}$, $\hat{I}_{Lc1}$) as a peak value product by the corresponding unity in-phase AC supply voltage to produce the desired reference AC supply currents ($i_{ref\text{-}sa}$, $i_{ref\text{-}sb}$, $i_{ref\text{-}sc}$) as illustrated in Fig.2. The reference compensation currents ($i_{a\text{-}Comp}$, $i_{b\text{-}Comp}$, $i_{c\text{-}Comp}$) are the difference between the actual value of the load current (i_{La}, i_{Lb}, i_{Lc}) and the corresponding desired reference supply currents [10–12]:

$$i_{a-Comp} = i_{La} - i_{ref-sa} \tag{1}$$

$$i_{b-Comp} = i_{Lb} - i_{ref-sb} \tag{2}$$

$$i_{c-Comp} = i_{Lc} - i_{ref-sc} \tag{3}$$

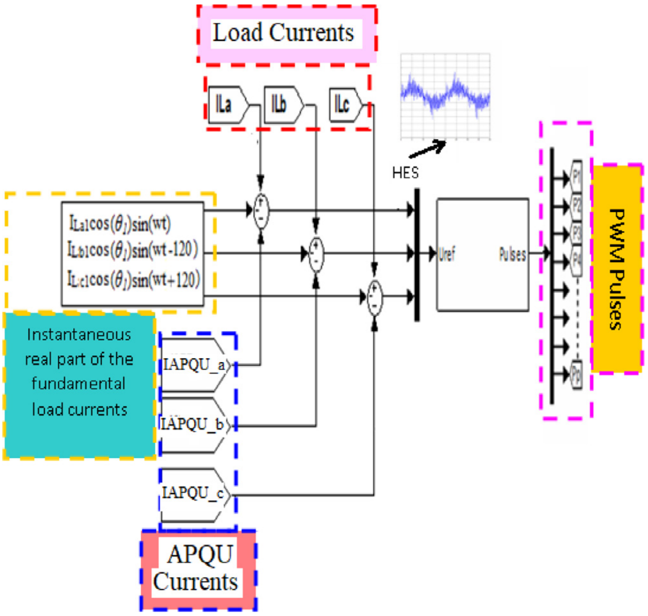


Fig. 2 Control. circuit of the APQU per phase.

where,

$$\left.\begin{aligned} i_{ref-sa} &= \hat{I}_{La1}\cdot\sin(wt)\\ i_{ref-sb} &= \hat{I}_{Lb1}\cdot\sin(wt-\tfrac{2\pi}{3})\\ i_{ref-sc} &= \hat{I}_{Lc1}\cdot\sin(wt+\tfrac{2\pi}{3})\end{aligned}\right\}\tag{4}$$

and

$$\left.\begin{aligned} \hat{I}_{La1} &= |\mathrm{I}_{\mathrm{La1}}\cdot\cos(\theta_{a1})\\ \hat{I}_{Lb1} &= |\mathrm{I}_{\mathrm{Lb1}}\cdot\cos(\theta_{b1})\\ \hat{I}_{Lc1} &= |\mathrm{I}_{\mathrm{Lc1}}\cdot\cos(\theta_{c1})\end{aligned}\right\}\tag{5}$$

where θ_{a1}, θ_{b1} and θ_{c1} are the phase angles of the fundamental load current amplitudes with respect to their supply voltages. The compensation current signal waveform is compared with the APQU current signal waveform ($i_{APQU\text{-}a}$, $i_{APQU\text{-}b}$, $i_{APQU\text{-}c}$) which produces harmonics error signal (HES). The HES is used as a reference signal which is compared with the carrier signal to produce PWM pulse signals.

$$HES=\begin{Bmatrix} i_{a-Comp} = i_{APQU\_a}\\ i_{b-Comp} = i_{APQU\_b}\\ i_{c-Comp} = i_{APQU\_c}\end{Bmatrix}\tag{6}$$

To explain effective functioning of the APQU ability for improving power quality of the LCC–HVDC system, suppose the system is supplied and worked with a three-phase balanced and symmetrical power sources with 1p.u and 0.95p.u line voltages at sending and receiving sides, respectively. Fig. 3 illustrates the supply phase voltage (v_{sa}) with its current (i_{sa}), and load current (i_{La}) with its fundamental component current (i_{La1}) of the 6-pulse LCC–HVDC system at both sides, without filter besides the required compensation current ($i_{a\text{-}Comp}$). The current (i_d) represents the desired supply current after connecting the APQU, while (i_q) is the desired fundamental current of the APQU. Also, HES waveform and its FFT analysis is illustrated in *Fig. 4*.

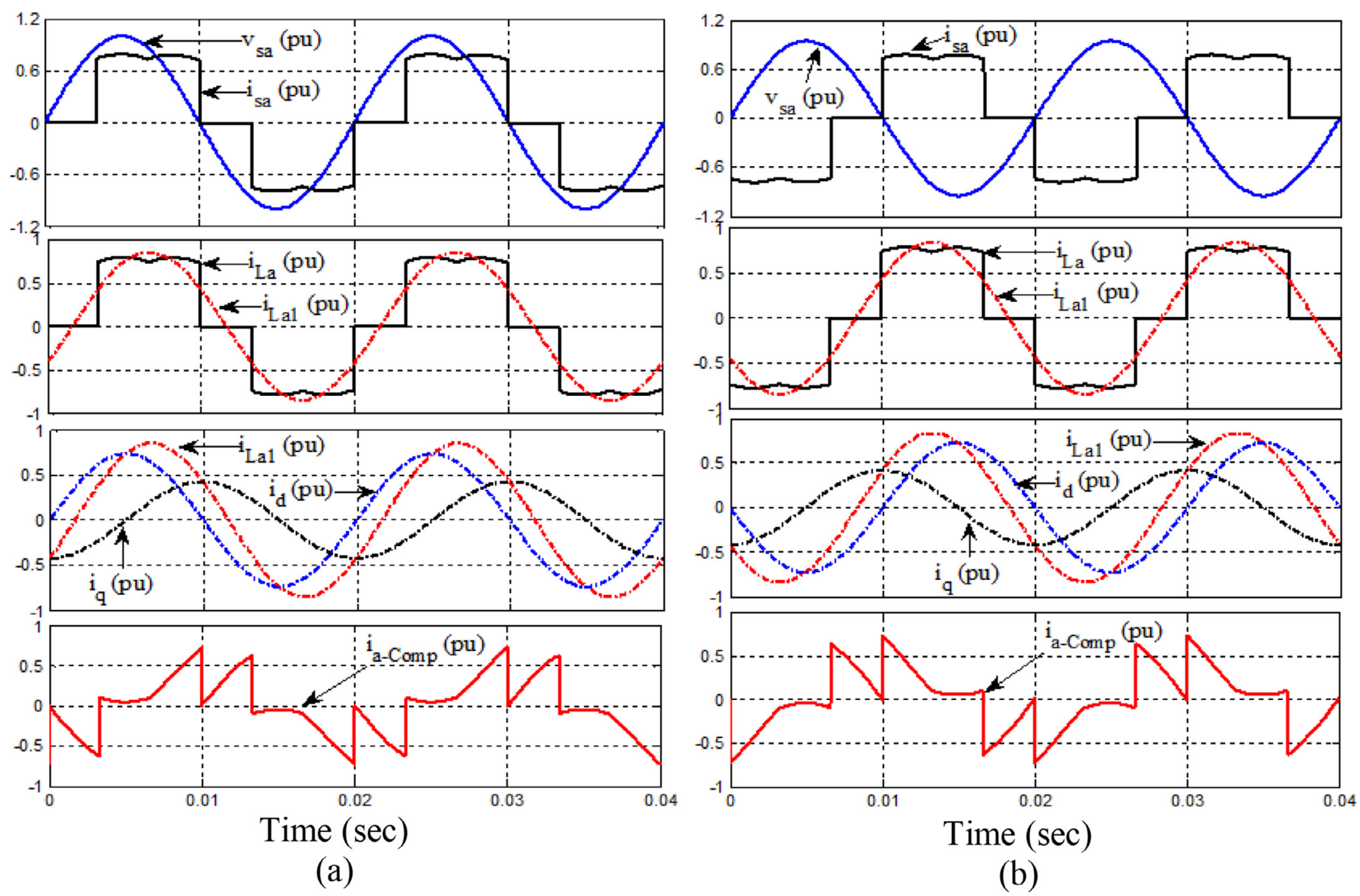


Fig. 3 Phase. supply voltage and current and load current of the LCC–HVDC system without filter at (a) sending and (b) receiving sides .

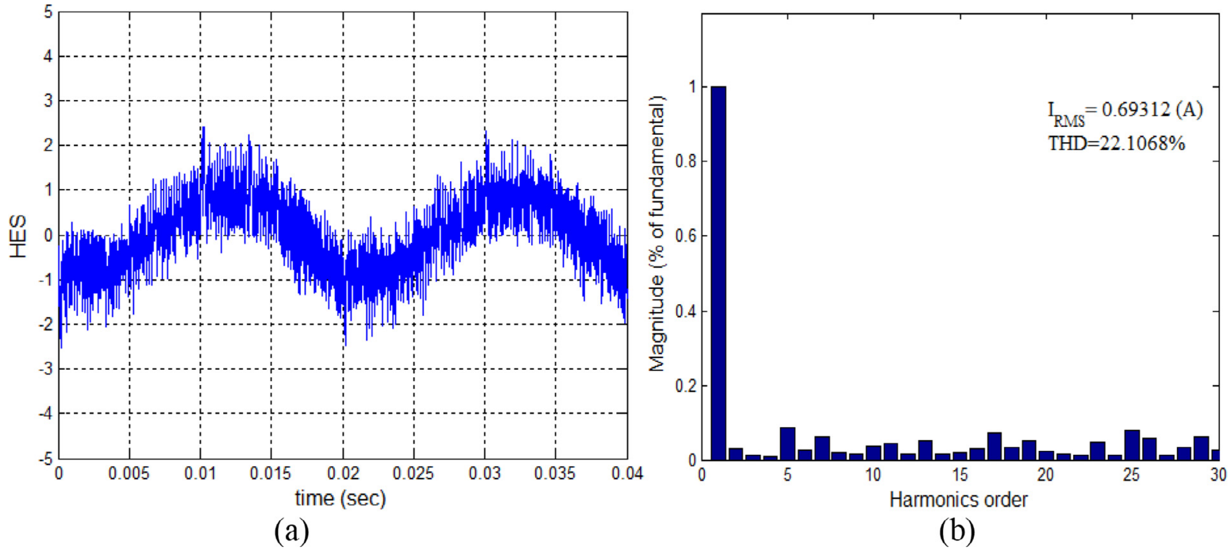


Fig. 4. (a) Harmonics error signal with its (b) FFT analysis.

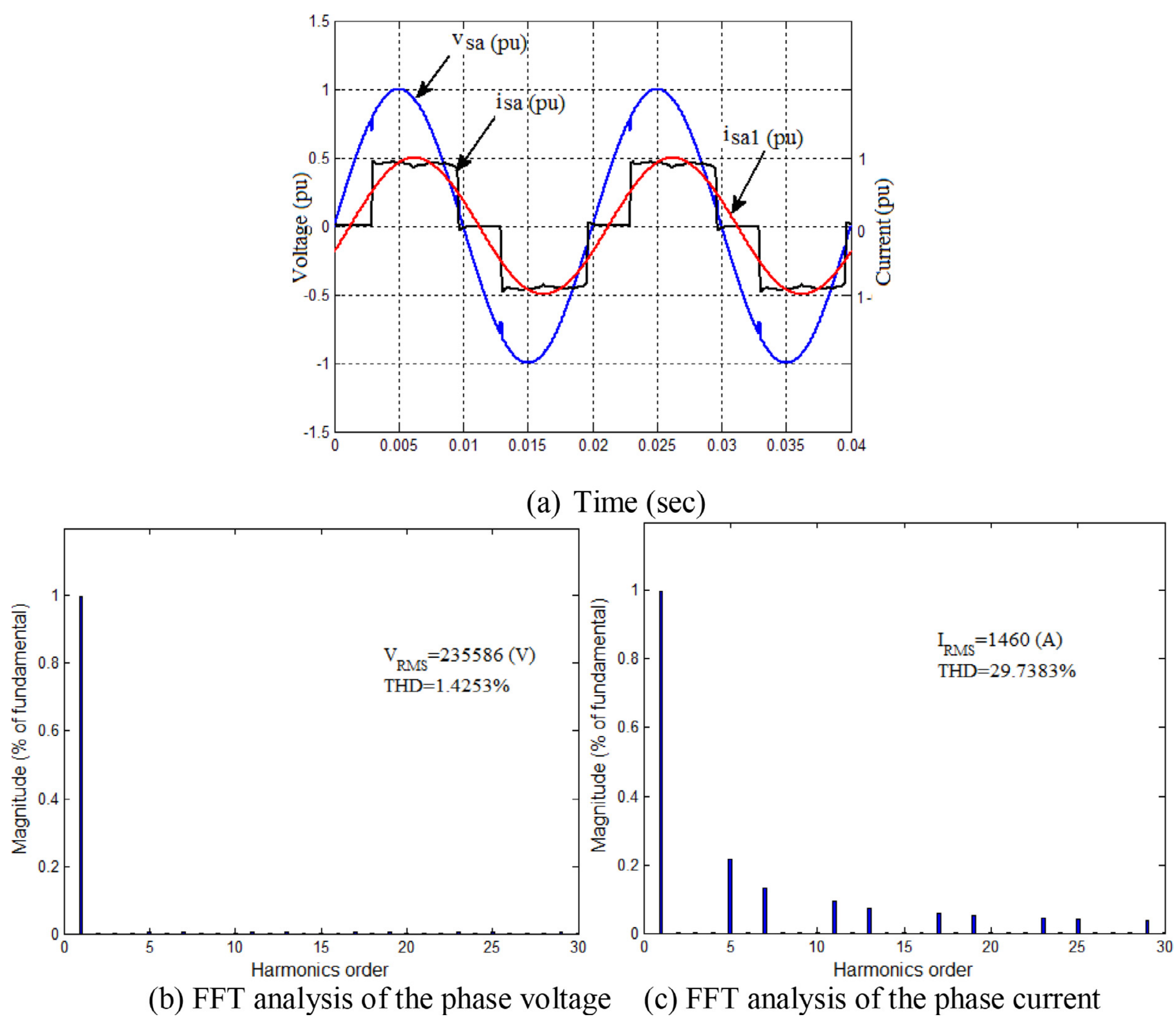
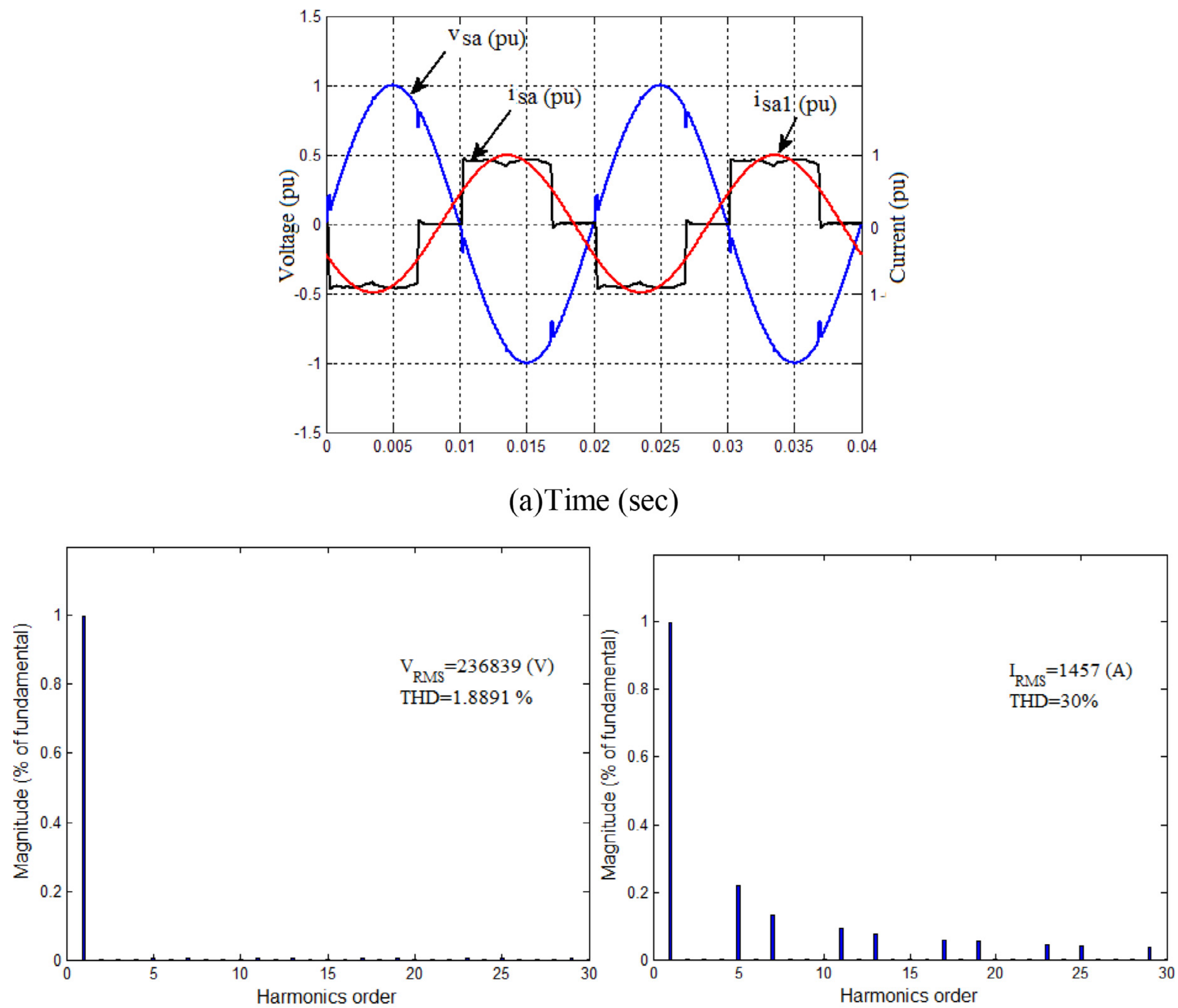


Fig. 5. Phase voltage and current of the 6-pulse LCC–HVDC link with its FFT analysis without APQU at sending end.



(b) FFT analysis of the phase voltage (c) FFT analysis of the phase current

Fig. 6. Phase voltage and current of the 6-pulse LCC–HVDC link with its FFT analysis without APQU at receiving end.

3. System description

In this paper, the nonlinear application selected to test the APQU with a classic 6-pulse LCC–HVDC link under different loading conditions. The system has been modeled by MATLAB/SIMULINK as a 500kV-1000MW-DC link, which connects 345 kV and 500 kV AC systems as illustrated in *Fig.1*. The three-phase transformers ratio is selected as (500/410) kV and (345/410) kV for the sending-end and receiving-end, respectively. The 6-pulse controlled converters are triggered with a firing angle (α) at sending-end side and an extinction angle (γ) at receiving-end side. The DC sides of the monopoles HVDC link is assumed to be supplying a transmission line of 300 km long having a 0.5H smoothing reactor. The desired DC power level (P_{dc}) is rated at 1000MW (2kA at 500 kV). The MVA and kV base values are assumed to be 1000MVA and 500 kV. Accordingly, a three phase APQU system is designed and implemented according to the MHPWM algorithm to compensate reactive power and reduce THD of the supply current for a wide range of P_{dc}. The APQU system based on 5-LCHBVSI and 7-LCHBVSI has been modelled and tested previously [11, 12]. The APQU based on three-phase 2-level H-bridge VSI is tested and built practically to improve the power quality of the 6-pulse LCC–HVDC system. The APQU based on the 2-level VSI is coupled through transformer (APQU_Tr), while it is coupled through a reactor [11, 12] for the 5-LCHBVSI and 7-LCHBVSI. The MHPWM algorithm control is tested based on real time control using dSpace DS1103.

4. Simulation results

The designed APQU based on three-phase 2-level VSI is simulated to show its steady-state and dynamic capabilities with the 6-pulse LCC–HVDC system. Selecting phase "a", the supply phase voltage (v_{sa}) and current (i_{sa}) waveforms with its FFT analysis at secondary sides of the sending-end and receiving-end transformers without and with the 2-level APQU at P_{dc} of 0.9 p.u. are shown in Fig.5, Fig.6, Fig.7 and Fig.8. These figures show clearly that the APQU system gives acceptable power quality with low THD and PF around unity. The FFT analysis explain the efectivness of the APQU for reducing the distortion in the supply voltage and current. The noise, or distortion, in the voltage and current waveforms is due to the high switching frequency of the inverter power switching devices. The distortion can be eliminated using a simple high pass filter. To check for which APQU type gives best power quality, APQU results based on 2-level, 5-LCHBVSI, and 7-LCHBVSI are compared. The THD and effective input PF without and with the APQU at different values of P_{dc} at sending and receiving sides are shown in Fig.9 and Fig.10. These results show that the effective input PF stays around unity and THD of the supply current is reduced at both sides. This demonstrates the effectiveness of the AQPU in improving the power quality of the HVDC system. The success of the AQPU is demonstrated by the AC distortion power waveform shown in Fig.11, which proves the THD results. As well, the reactive power supplied by

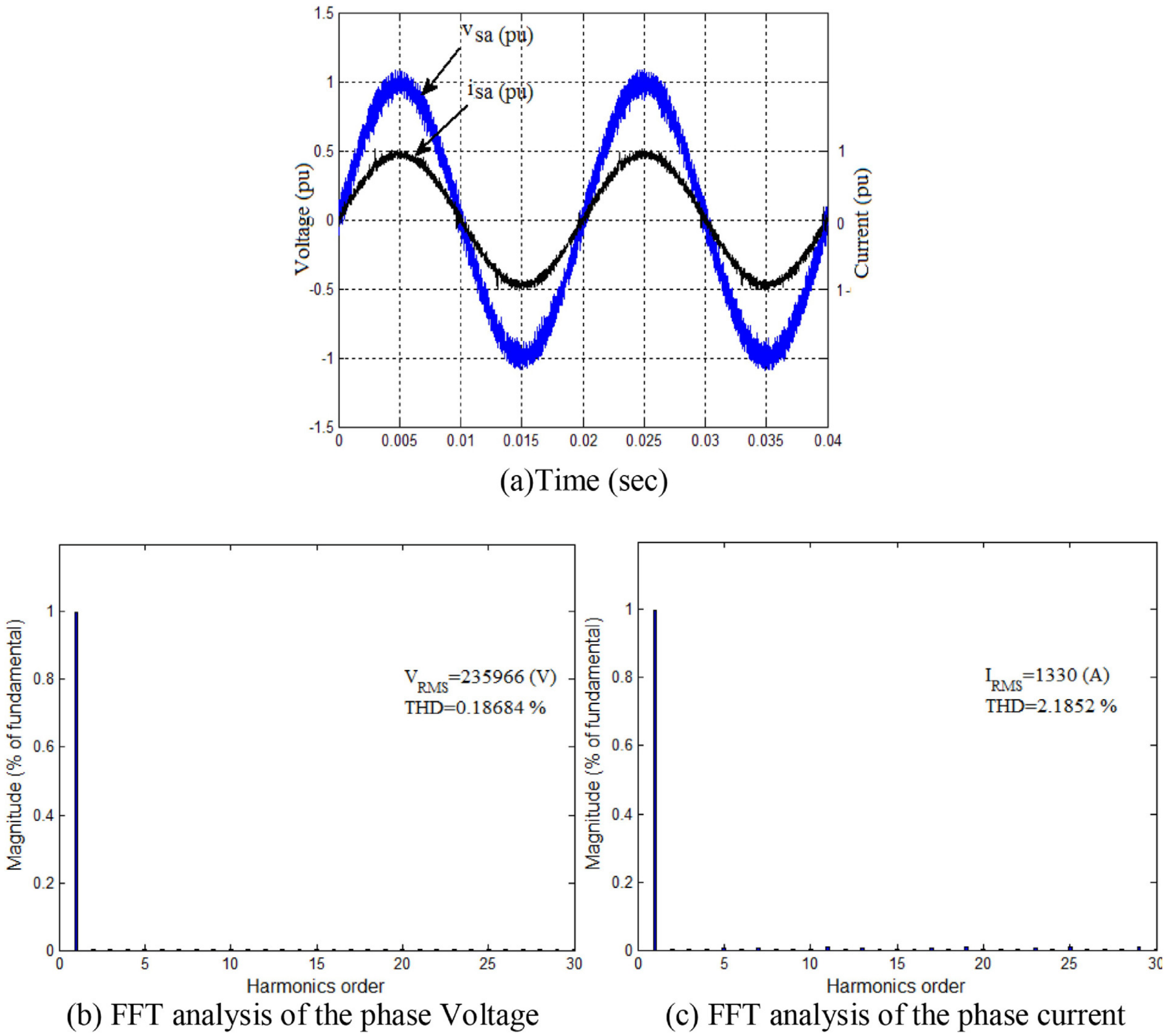


Fig. 7. Phase voltage and current of the 6-pulse LCC–HVDC link with its FFT analysis and the 2-level APQU at sending end.

the AC source at sending and receiving sides shown inFig.12 is almost disappeared which verify effectiveness of the AQPU in improving PF. At constant P_{dc}, the THD of the supply current at sending-end side reduces about 91.5%, 94% and 97.4% after connecting the APQU depending on 2-level, 5-level and 7-level cascade H-bridge VSI, respectively. While at the receiving-end side, the THD improves to about 91%, 96.5% and 95.8%, respectively. Also the effective input PF is increased by about 12.4% at sending-end side and 15.44% at receiving-end side. These results show that the 6-pulse LCC–HVDC link performance has improved after connecting the APQU. The firing angles of the HVDC converters vary between 23.80– 26.40 at sending side and between 152.8°–153.8°at receiving side when P_{dc} varies between 0.3–1pu.

Based on simulation results, the APQU using 2-level MAPF have significat improvement in power quality, also using 5-level and 7-level, with their complexity, give slightly better results than 2-level MAPF. This is due to the operation of the multilevel inverter with a lower switching frequency and hence the stress on power switching devices is lower as compared with the conventional inverter. Also the output voltage generated by the multilevel inverter has low distortion.

5. Experimental results

The hardware circuits of the 6-pulse LCC–HVDC with the APQU and MHPWM control algorithm are developed and tested experimentally. The control circuit of the APQU has been built using the dSPACE DS1103 board. The Laboratory setup has been built based on power circuit, control system, and measurement devices. The practical circuit shown in Fig.13(a) is adopted. The power circuit of the APQU is built based on three-phase 2-level H-bridge VSI. The block diagram of the overall system is shown in Fig.13(b). The experimental test bench circuit is shown in Fig.13(c).

The control system is tested in a real time in order to check and validate its performance. The practical supply phase voltage and current waveforms without and with the APQU circuit for different firing angles are monitored at the sending and receiving sides as shown in Fig.14, Fig.15 and Fig.16. These results show that the current is in phase with the voltage, which demonstrates the effectiveness of the proposed APQU. As expected, the supply voltage and current are almost sinusoidal. Experimental results prove that the AC current harmonics can be significantly minimized under different operating conditions.

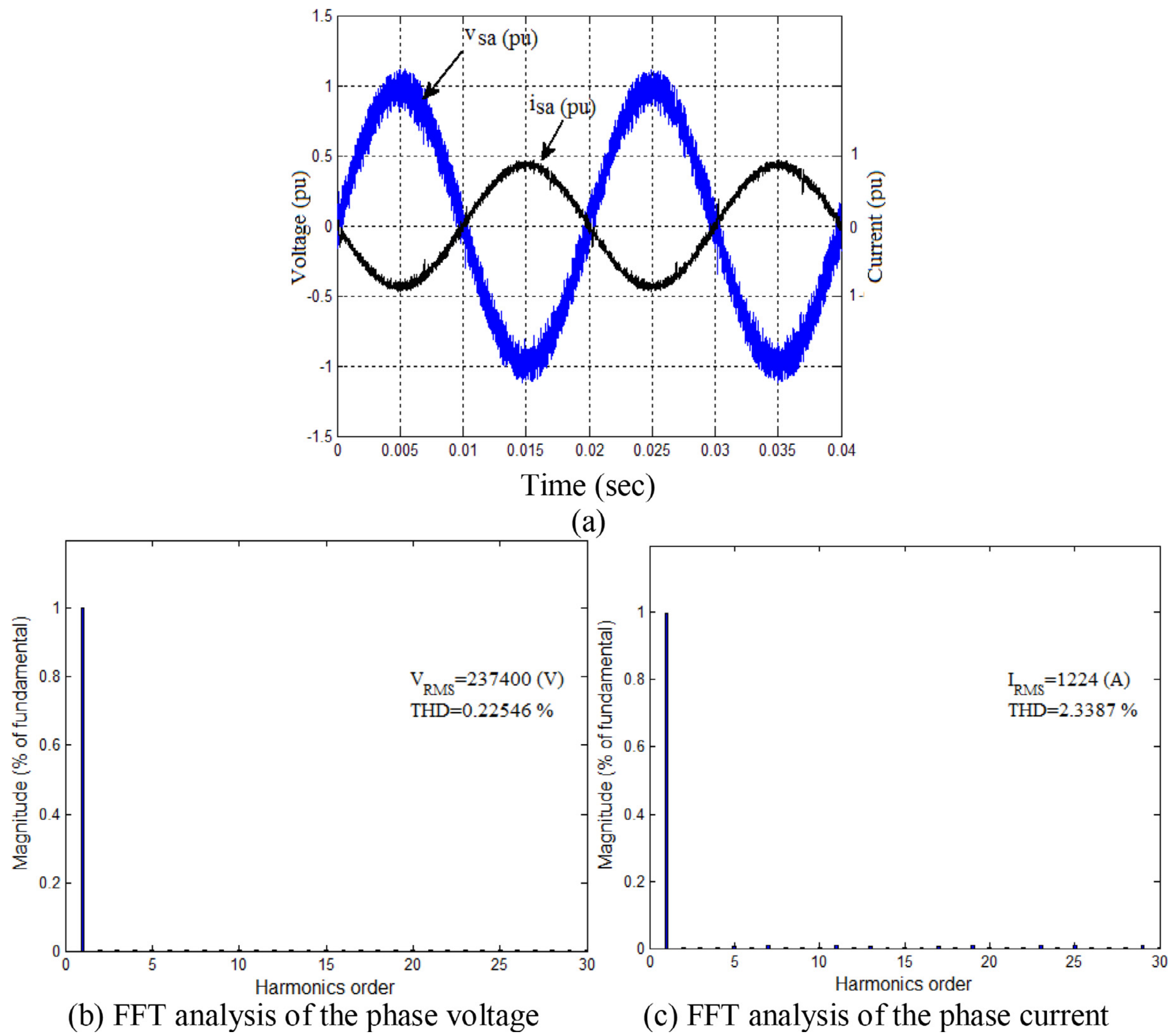


Fig. 8. Phase voltage and current of the 6-pulse LCC–HVDC link with its FFT analysis and the 2-level APQU at receiving end.

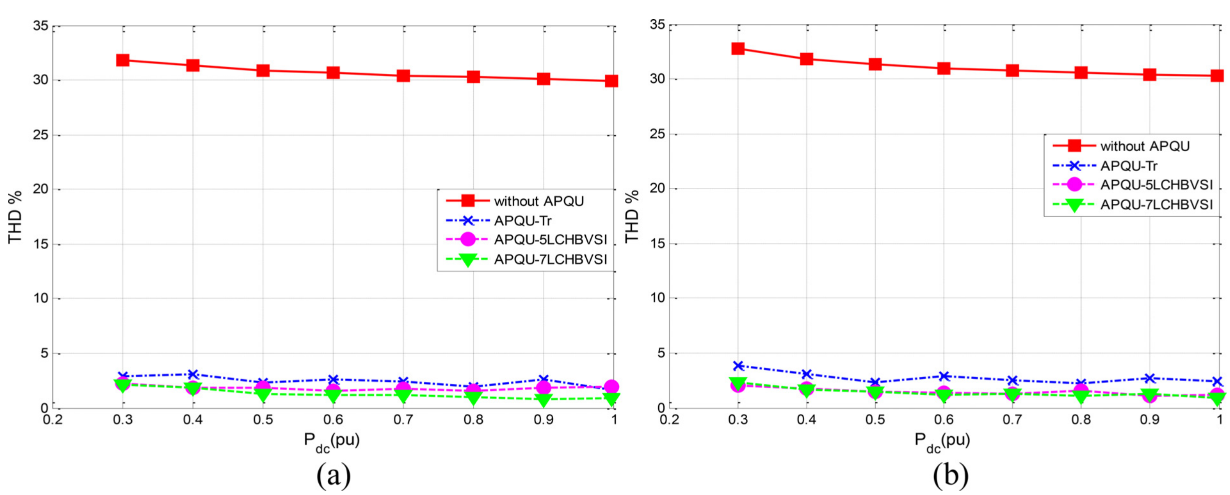


Fig. 9. THD waveforms of the input AC current of the 6-pulse LCC–HVDC link without and with the APQU at (a) sending and (b) receiving ends.

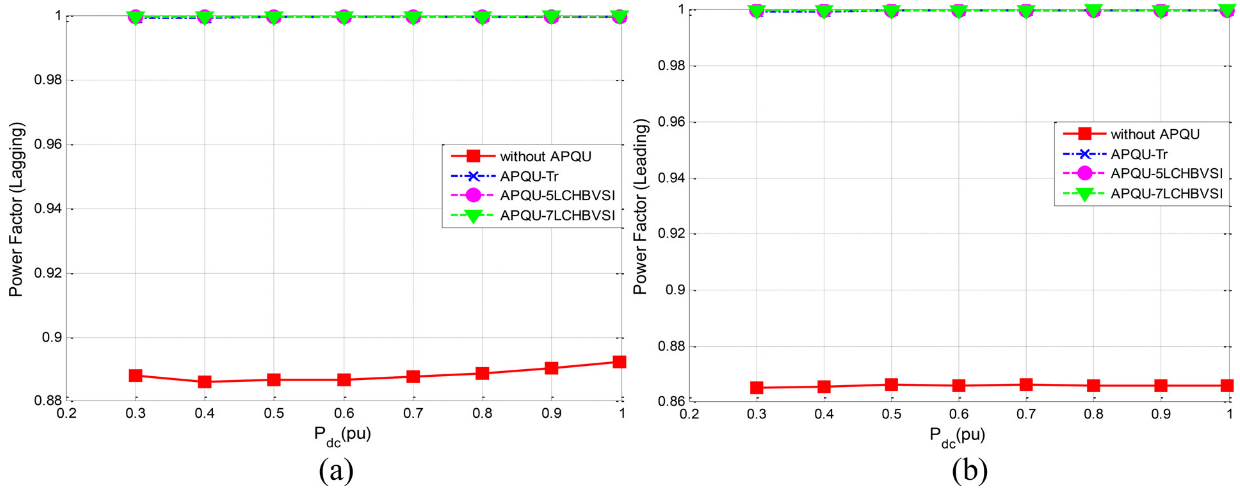


Fig. 10. Effective input PF without and with the APQU at (a) sending and (b) receiving ends.

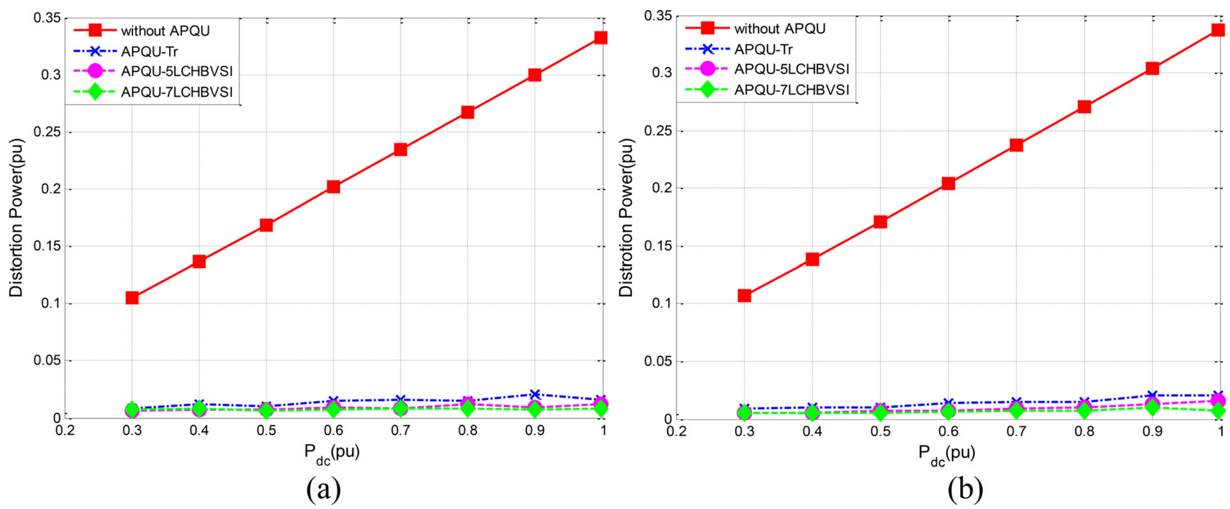


Fig. 11. Distortion power levels in the AC supply current without and with the APQU at (a) sending and (b) receiving ends.

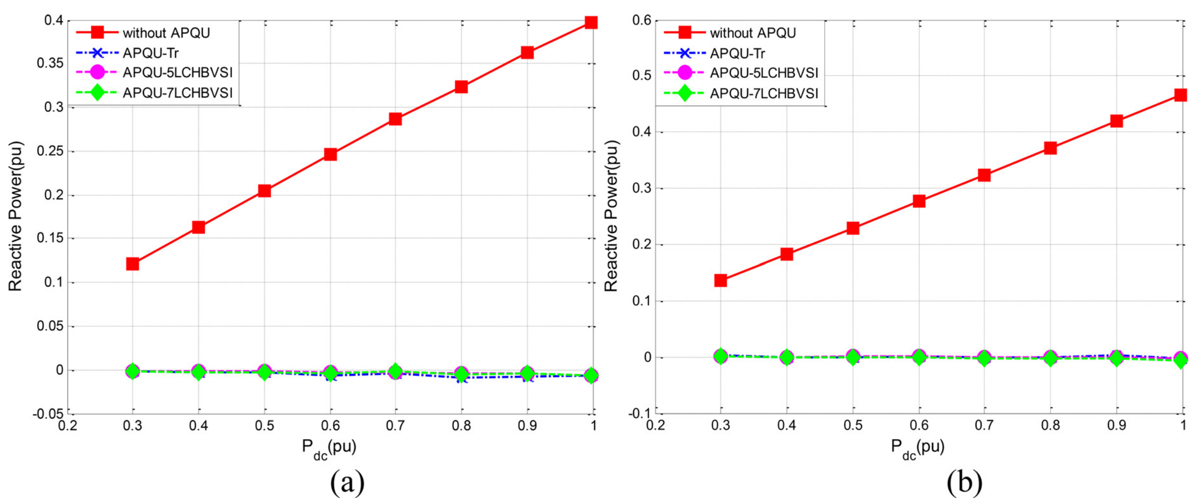
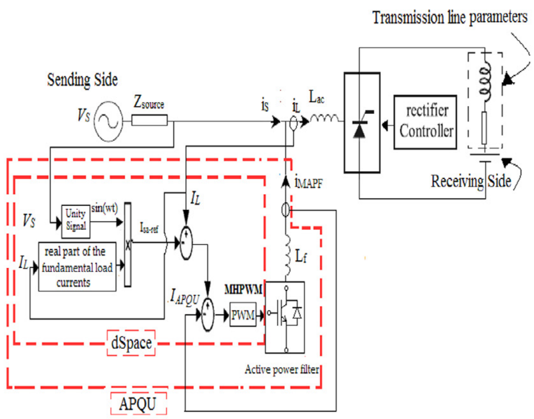
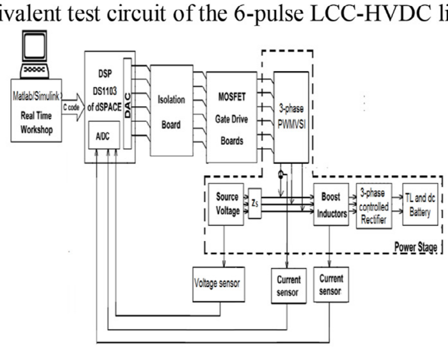


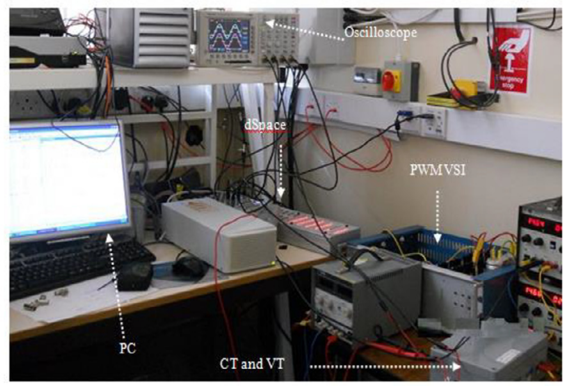
Fig. 12. Reactive power without and with the APQU at (a) sending and (b) receiving ends.



(a) Practical equivalent test circuit of the 6-pulse LCC-HVDC link with the APQU.

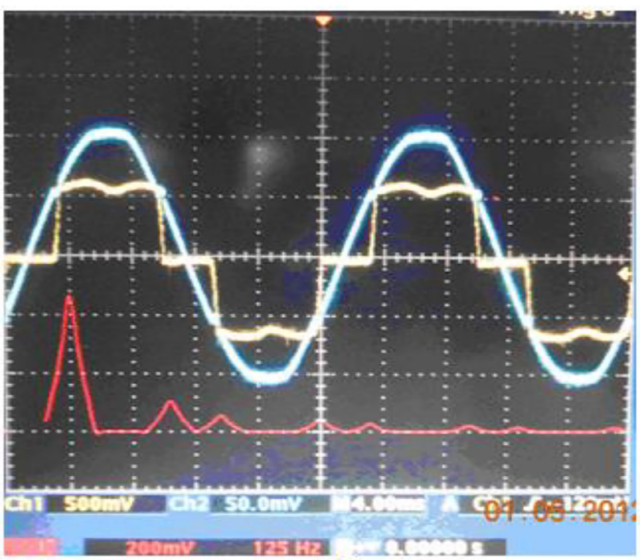


(b) Block diagram of the overall system.

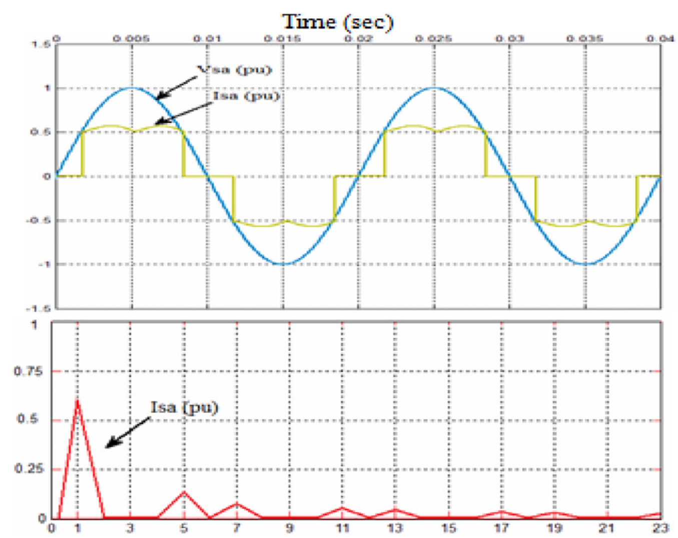


(c) The test bench

Fig. 13. Experimental set-up of the 6-pulse LCC–HVDC link with the APQU and dSpace controller.

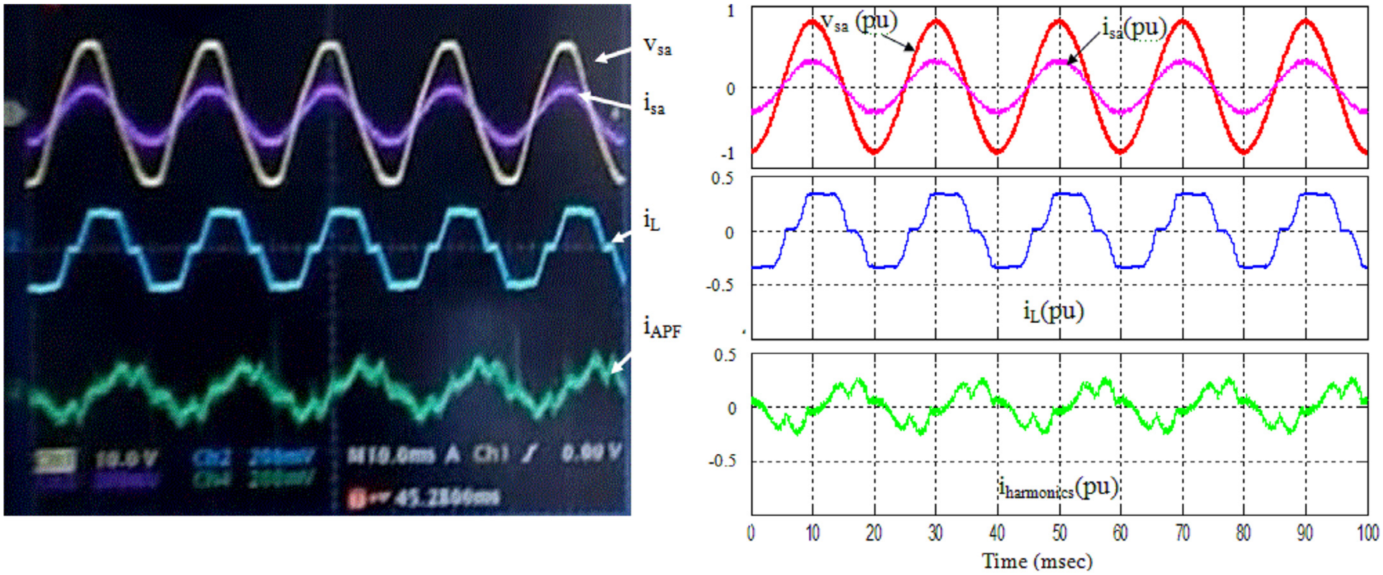


(a)

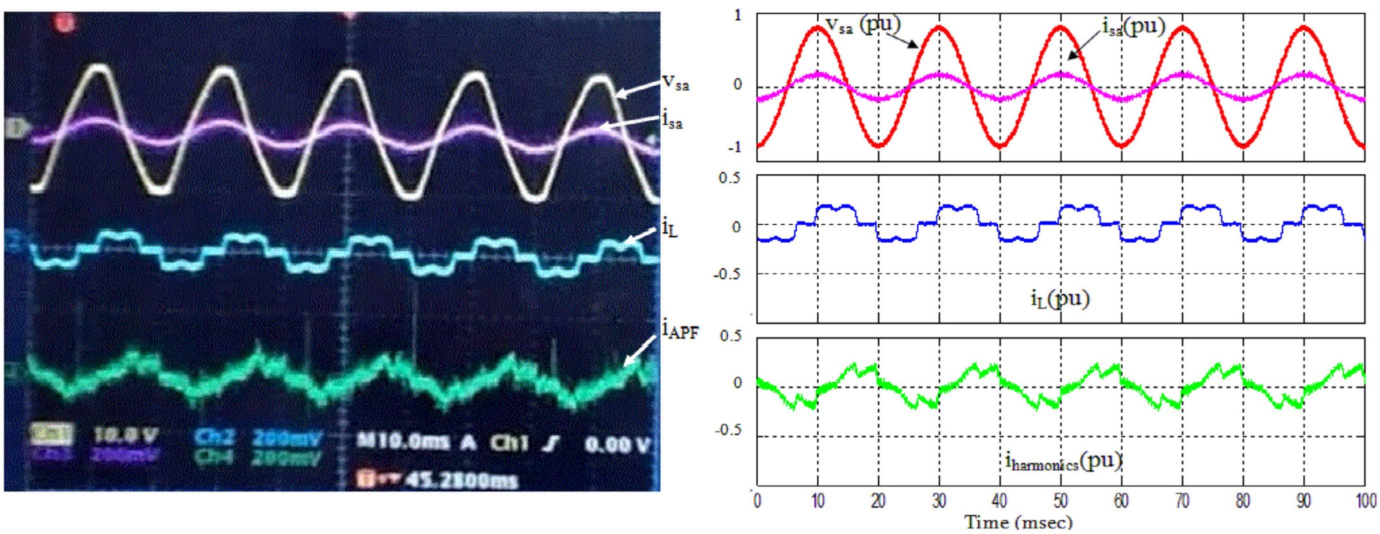


(b)

Fig. 14. (a) Experimental and (b) simulation results of the input phase voltage and current without active power quality unit at 0° firing angle.



(a)



(b)

Fig. 15. Experimental and simulation results of the input phase voltage and current in the rectification mode at firing angle (α) of (a) 45 and (b) 57°.

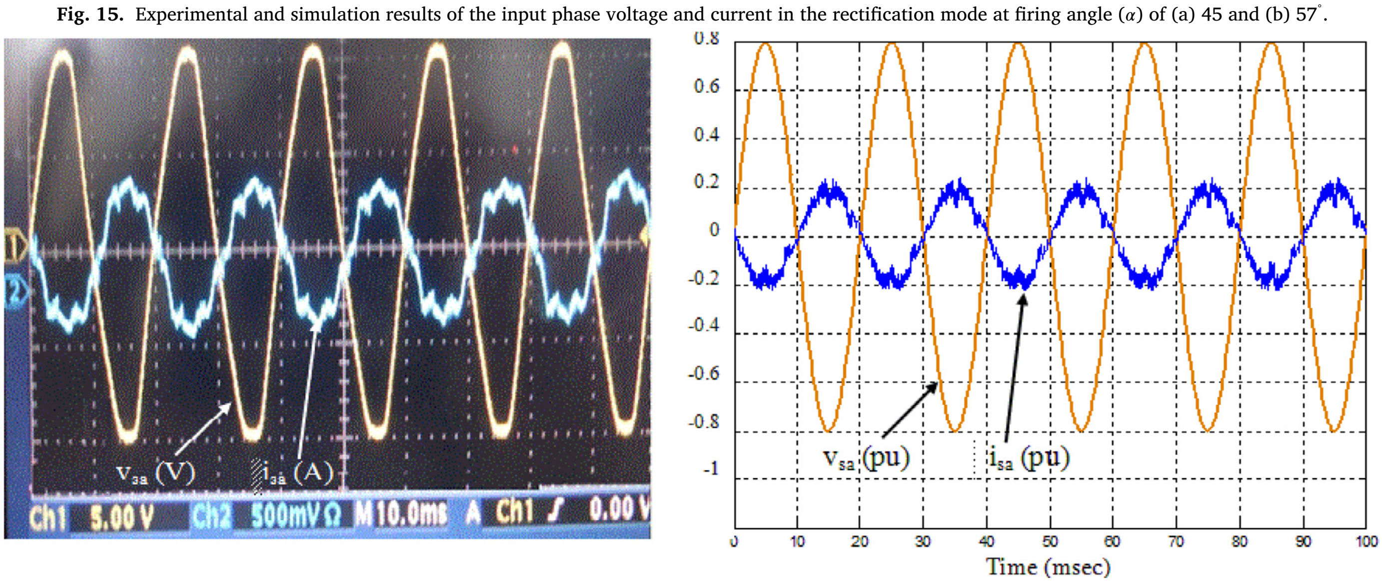


Fig. 16. Experimental and simulation results of the input phase voltage and current in the inversion mode at α=155°.

6. Conclusions

This paper proposes an APQU for improving the performance of the 6-pulse LCC–HVDC transmission systems. The proposed system is simulated in MATLAB/SIMULINK environment. An experimental laboratory prototype is then developed and tested without and with the APQU. The APQU is designed to minimize harmonics and compensate fundamental reactive power components for a wide range of operating line current conditions. Test results demonstrate effectiveness of the APQU that makes the source current almost sinusoidal and in-phase with the AC supply voltage. The MHPWM algorithm has been used with the APQU based on 2-level, 5-level and 7-level cascade H-bridge PWM VSI to improve the power quality of the 6-pulse LCC–HVDC system. The results show that the power quality improvements are within IEEE standards for a wide range of DC power flow through the transmission line. For validation purposes, the MHPWM algorithm is implemented practically using the benefits and ability of the dSPACE DS1103 board to perform the proposed control strategy in real-time. The real-time experimental results with an on-line variation of thyristor firing angles of the 6-pulse LCC–HVDC system model show that the real-time phase voltage and current are almost free of harmonics and the supply current becomes in-phase with its corresponding voltage. This demonstrates the effectiveness of the proposed APQU.

Declaration of Interest Statement

I, on behalf of my co-authors, Rakan Khalil ANTAR, Basil M. Saied, Ghanim A. Putrus, and Rafid A. Khalil, of the manuscript entitled, “Treating the Impacts of Connecting HVDC Link Converters with AC Power System Using Real-Time Active Power Quality Unit”, hereby declare that there is no conflict of interest regarding the publication of this article in the Elsevier’s e-Prime – Advances in Electrical Engineering, Electronics and Energy.

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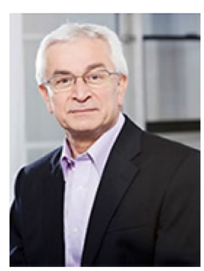

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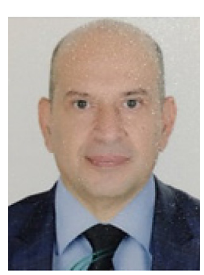

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